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Long Baseline Neutrino Experiments with Two-Detector Setup

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I discuss why and how powerful is the two-detector setting in neutrino oscillation experiments. I cover three concrete examples: (1) reactor θ_{13} experiments, (2) T2KK, Tokai-to-Kamioka-Korea two-detector complex for measuring CP violation, determining the neutrino mass hierarchy, and resolving the eight-fold parameter degeneracy, (3) two-detector setting in a neutrino factory at baselines 3000 km and 7000 km for detecting effects of non-standard interactions (NSI) of neutrinos.

1. Introduction

Unified understanding of the physics of quark and lepton flavor mixings would be the most important goal for the contemporary flavor physics. Though we started to grasp the structure of the flavor mixing matrix, the MNS matrix¹, there is a long way to go. Unlike the quark sector in which the dominant mechanism of CP violation is identified², the very existence of CP violation itself remains a mystery in the lepton sector. Therefore, looking for leptonic CP violation will be one of the crucial key elements in planning the next generation neutrino experiments. Moreover, various studies indicated that uncovering leptonic CP violation is highly challenging experimentally. Therefore, strategic thoughts on how to make the goal may be of some use. This is the only reason I can think of why this talk with such a technical title (though it was given by the organizer) may be worth to be presented in the flavor physics conference.

Yet, I will try to cover the related topics in a slightly wider context under the hope that it serves for illuminating the merits of the two-detector setting even more clearly. Namely, I address the three concrete examples of the two-detector setting;^a

- Reactor θ_{13} experiments^{3,4}
- T2KK, Tokai-to-Kamioka-Korea identical two-detector complex for measuring CP violation, determining the neutrino mass hierarchy, and resolving the eight-fold parameter degeneracy^{5,6}
- Two-detector setting in a neutrino factory (3000 km, 7000 km) for detecting non-standard interactions (NSI) of neutrinos⁷

^a We define the two-detector setting as composed of two detectors excluding a front detector which measures un-oscillated neutrino flux or monitors beam.

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Before entering into the discussions let us raise a general question; What is good in two-detector setting? The answer is:

- The systematic errors cancel between the two detectors.
- Measurement at the two detectors can have synergy effects whose significance, however, varies a lot in case by case.

2. Reactor θ_{13} Experiments

With regard to multi detector reactor experiment, there is in fact, an ancestor experiment, the Bugey experiment⁸ which utilized the three detectors albeit not quite identical ones. It was proposed in^{3,4} that the only practical way to measure a small depletion due to θ_{13} is to place two identical detectors one at a near (100-300 m) and the other at a far (1-2 km) locations. Controlling the systematic errors and cancelation of them between the two detectors is the key to such difficult measurement. Now it becomes a “customary” design for the reactor θ_{13} experiments and the principle is employed in all the projects in construction⁹. See¹⁰ for other projects.

3. T2KK; Tokai-to-Kamioka-Korea Two Detector Complex

In the context of accelerator neutrino experiments a proposal of two detector setting appeared in the Brookhaven proposal¹¹. The authors of Ref.¹² discussed two detector methods for measuring leptonic CP violation by observing neutrino oscillation “phase” at two different locations. A concrete realization of this principle was proposed^{5,6} in a form of identical two-detector setting using two megaton class detectors in Kamioka and Korea receiving an intense neutrino beam from J-PARC, the Tokai-to-Kamioka-Korea (T2KK) project. See¹³ for more about the project.

I just give a sketchy description here about how the T2KK two detector setting is powerful. For more details, in particular, for a fuller description of the sensitivities to CP violation, the mass hierarchy, and resolution of the eight-fold parameter degeneracy^{14,15,16}, see^{5,6}. Figure 1 shows how the spectrum information is powerful to determine CP phase δ resolving the $\delta \leftrightarrow \pi - \delta$ ambiguity. Comparison between the left and the right panels indicates that the T2KK setting is more efficient to resolve the ambiguity by comparing the yields at the two detectors at the two different locations.

It is often said that resolution of the mass hierarchy can be done by using long baseline thanks to the earth matter effect to neutrino oscillation. Though it is of course true, Fig. 2 indicates that it is *not* the whole story. The left panels are for the T2KK setting with each 0.27 Mton fiducial mass detectors placed in Kamioka and Korea, whereas the right panels are for Korea only setting with 0.54 Mton fiducial mass. The figure demonstrates that the two detector comparison has a higher resolving power of the neutrino mass hierarchy than the Korea only setting. Though I do not elaborate, resolution of the θ_{23} octant degeneracy is also merited by the two detector setting which does (Korea) and does not (Kamioka)

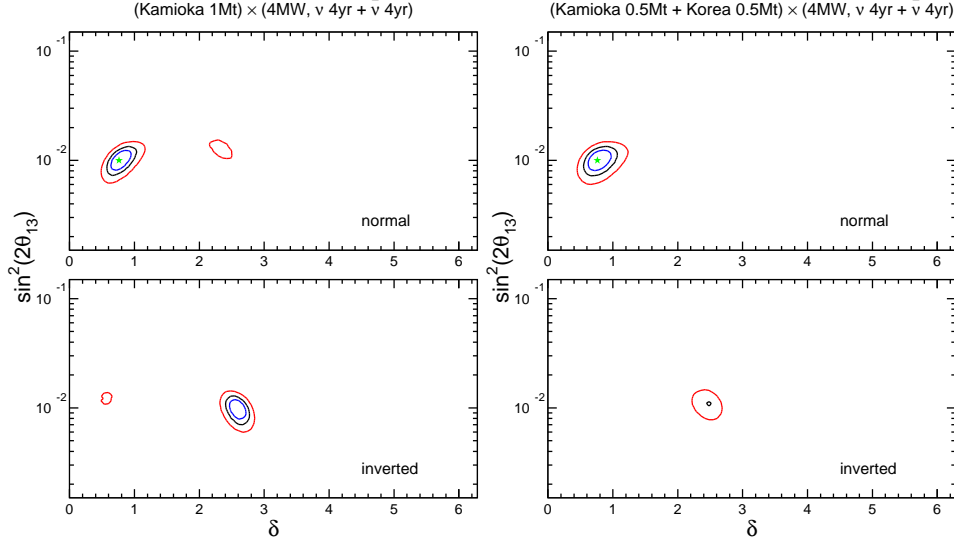


Fig. 1. The region allowed in $\delta - \sin^2 2\theta_{13}$ space by 4 years of neutrino and antineutrino running in T2K II (left panels), and the Kamioka-Korea two detector setting (right panels). They are taken from the supplementary figures behind the reference⁵ to which the readers are referred for details of the analysis. Notice that the standard setting in T2K II, 2 (6) years of neutrino (antineutrino) running, leads to a very similar results (as given in [?]) to the one presented in the left panel of this figure. The true solutions are assumed to be located at $(\sin^2 2\theta_{13} \text{ and } \delta) = (0.01, \pi/4)$ with positive sign of Δm_{31}^2 , as indicated as the green star. The intrinsic and the Δm_{31}^2 -sign clones appear in the same and the opposite sign Δm_{31}^2 panels, respectively. Three contours in each figure correspond to the 68% (blue line), 90% (black line) and 99% (red line) C.L. sensitivities, respectively.

feel the solar oscillation effect. There is an interesting competition and synergy between the T2KK and the reactor-accelerator combined method^{4,17} for lifting the θ_{23} degeneracy. The former (latter) is more powerful at small (large) θ_{13} .

4. Probing Non-Standard Neutrino Interactions at Neutrino Factories

My last topics is the two detector setting in neutrino factory, one at ~ 3000 km and the other at ~ 7000 km, the latter so called the magic baseline¹⁸. The idea of the setting was originated from the consideration of how the intrinsic $\theta_{13} - \delta$ degeneracy can be lifted^{14,18}. It has been also shown that a detector at the magic baseline has an extremely high sensitivity for measuring the average earth matter density (assuming the MSW theory) along the neutrino trajectory^{19,20}.

Therefore, it is entirely natural to think about the possibility that neutrino factory with two detector setting can serve for a powerful hunting tool for possible non-standard interactions (NSI)^{21,22} possessed by neutrinos. It is conceivable that such NSI would arise if there exists new physics scale at TeV ranges. They may be parametrized by four Fermi interactions; $\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\varepsilon_{\alpha\beta}^F G_F (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta) (\bar{f} \gamma^\mu P f)$. One expects by dimensional counting that NSI

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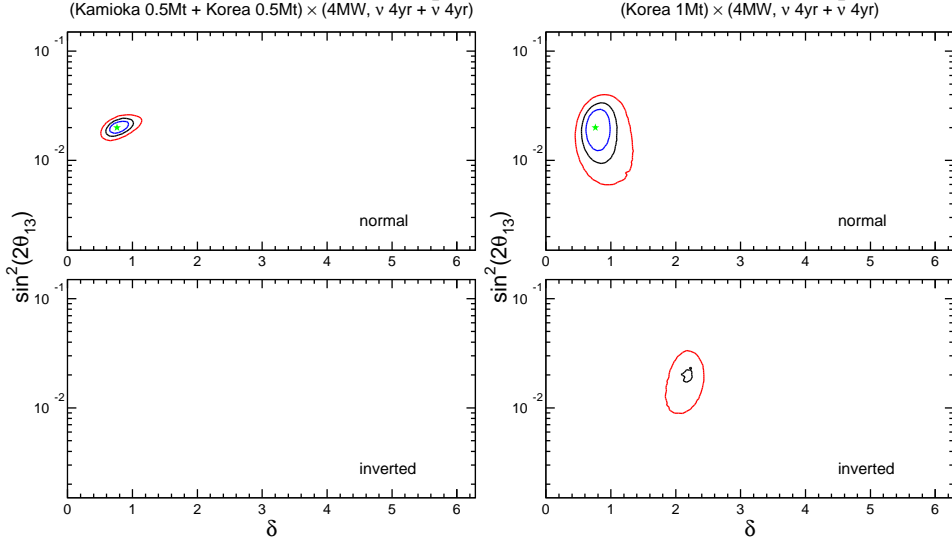


Fig. 2. The similar sensitivity plot as in Fig. 1. The left panels are for T2KK and the right panels are for a single 0.54 megaton detector placed in Korea.

coefficients $\varepsilon_{\alpha\beta}^{fP}$ and therefore the effective interaction $\varepsilon_{\alpha\beta} \equiv \sum_{f,P} \frac{n_f}{n_e} \varepsilon_{\alpha\beta}^{fP}$ which appears in the neutrino evolution equation would have a size of the order of $(m_Z/M_{np})^2 \sim 10^{-2}$ (10^{-4}) for $M_{np} = 1$ (10) TeV. Then, neutrino factory is the best thinkable machine to explore such tiny effects of NSI. There exist numerous references which are devoted to existing constraints on NSI and how to probe it further by future experiments. See e.g., the references quoted in ⁷.

Now, I present in Fig. 3 the regions allowed by measurement of detectors at 3000 km (upper panels), 7000 km (middle panels), and two detectors combined (bottom panels). The left, middle, and the right three panels are for the cases with $\varepsilon_{ee}-\varepsilon_{e\tau}$, $\varepsilon_{\tau\tau}-\varepsilon_{e\tau}$, and $\varepsilon_{ee}-\varepsilon_{\tau\tau}$, respectively. We notice that the detector at 3000 km alone does not have good sensitivities to NSI. This statement is also true for the detector at 7000 km though the sensitivity to the off diagonal elements is much better than that of 3000 km detector; It is the very motivation for placing the detector at the magic baseline. The reason for such disparity in the sensitivities to the diagonal and the off diagonal elements of $\varepsilon_{\alpha\beta}$ is explained in ⁷ based on the analytic formula derived there. The synergy effect of combining the intermediate and the far detectors is remarkable. The allowed regions scattered in wide ranges in the top (3000 km) and the middle (7000 km) panels combine into a much smaller region in the bottom panel. To the best of my knowledge, such a synergy effect so significant as in Fig. 3 is rarely seen.

The remaining (important!) issue in the neutrino factory measurement of NSI is that the sensitivity to θ_{13} is largely lost because of confusion with NSI ²³. We were able to show that this problem is also solved by the same two detector setting. See

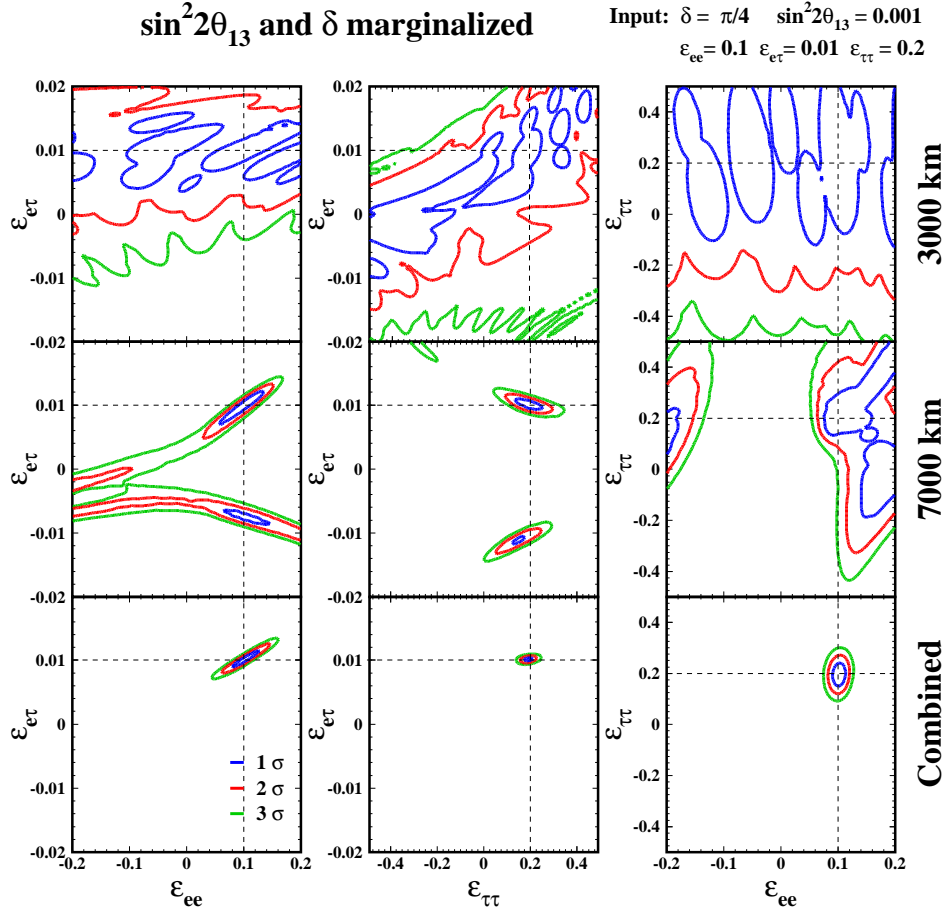


Fig. 3. Allowed regions projected into the plane of 2 NSI parameters, ε_{ee} - $\varepsilon_{e\tau}$ (left panels), $\varepsilon_{e\tau}$ - $\varepsilon_{\tau\tau}$ (middle panels) and ε_{ee} - $\varepsilon_{\tau\tau}$ (right panels) corresponding to the case where the input parameters are as follows: $\sin^2 2\theta_{13} = 0.001$, $\delta = \pi/4$, $\varepsilon_{e\tau} = 0.01$, $\varepsilon_{ee} = 0.1$, and $\varepsilon_{\tau\tau} = 0.2$. The neutrino energy is $E_\mu = 50$ GeV and the baseline is taken as $L = 3000$ km (upper panels), 7000 km (middle horizontal panels) and combination (lower panels). The thin dashed lines are to indicate the input values of $\varepsilon_{\alpha\beta}$. The fit was performed by varying freely 4 parameters, θ_{13} , δ and 2 ε 's with θ_{13} and δ being marginalized. The number of muons decays per year is 10^{21} , the exposure considered is 4 (4) years for neutrino (anti-neutrino), and each detector mass is assumed to be 50 kt. Notice that this figure supplements Fig. 16 of ⁷ which uses the same parameters as this figure except for the input value of CP phase, $\delta = 3\pi/2$.

Ref. ⁷ for further details. Therefore, we have concluded (I believe for the first time) that the results obtained in this paper open the door to the possibility of using *neutrino factory as a discovery machine for NSI*, while keeping its function of precision measurement of lepton mixing parameters. Finally, I would like to emphasize that discovery of physics beyond the neutrino mass incorporated Standard Model would be much more exciting goal for remote future neutrino experiments.

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References

1. Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28**, 870 (1962).
2. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
3. V. Martemyanov, L. Mikaelyan, V. Sinev, V. Kopeikin and Yu. Kozlov, Phys. Atom. Nucl. **66**, 1934 (2003) [Yad. Fiz. **66**, 1982 (2003)] [arXiv:hep-ex/0211070].
4. H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue and F. Suekane, Phys. Rev. D **68**, 033017 (2003) [Erratum-ibid. D **70**, 059901 (2004)] [arXiv:hep-ph/0211111].
5. M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, Phys. Rev. D **72**, 033003 (2005) [arXiv:hep-ph/0504026].
6. T. Kajita, H. Minakata, S. Nakayama and H. Nunokawa, Phys. Rev. D **75**, 013006 (2007) [arXiv:hep-ph/0609286].
7. N. Cipriano Ribeiro, H. Minakata, H. Nunokawa, S. Uchinami and R. Zukanovich Funchal, arXiv:0709.1980 [hep-ph].
8. Y. Declais *et al.*, Nucl. Phys. B **434**, 503 (1995).
9. F. Ardellier *et al.* [Double Chooz Collaboration], arXiv:hep-ex/0606025; X. Guo *et al.* [Daya Bay Collaboration], arXiv:hep-ex/0701029; For RENO Collaboration, see, <http://neutrino.snu.ac.kr/RENO/>; K. K. Joo, Talk at Neutrino Oscillation Workshop (NOW2006), Conca Specchiulla (Otranto, Lecce, Italy), September 9-16, 2006.
10. K. Anderson *et al.*, arXiv:hep-ex/0402041.
11. D. Beavis *et al.* (E889 Collaboration), Physics Design Report, BNL No. 52459, April 1995.
12. H. Minakata and H. Nunokawa, Phys. Lett. B **413**, 369 (1997) [arXiv:hep-ph/9706281].
13. The first workshop: <http://newton.kias.re.kr/~hepph/J2K/>
The second workshop: <http://t2kk.snu.ac.kr/>
The third workshop: <http://www-rcn.icrr.u-tokyo.ac.jp/workshop/T2KK07/>
14. J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. Mena, Nucl. Phys. B **608**, 301 (2001) [arXiv:hep-ph/0103258].
15. H. Minakata and H. Nunokawa, JHEP **0110**, 001 (2001) [arXiv:hep-ph/0108085].
16. G. L. Fogli and E. Lisi, Phys. Rev. D **54**, 3667 (1996) [arXiv:hep-ph/9604415].
17. K. Hiraide, H. Minakata, T. Nakaya, H. Nunokawa, H. Sugiyama, W. J. C. Teves and R. Zukanovich Funchal, Phys. Rev. D **73**, 093008 (2006) [arXiv:hep-ph/0601258].
18. P. Huber and W. Winter, Phys. Rev. D **68**, 037301 (2003) [arXiv:hep-ph/0301257].
19. H. Minakata and S. Uchinami, Phys. Rev. D **75**, 073013 (2007) [arXiv:hep-ph/0612002].
20. R. Gandhi and W. Winter, Phys. Rev. D **75**, 053002 (2007) [arXiv:hep-ph/0612158].
21. L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
22. Y. Grossman, Phys. Lett. B **359**, 141 (1995) [arXiv:hep-ph/9507344].
23. P. Huber, T. Schwetz and J. W. F. Valle, Phys. Rev. Lett. **88**, 101804 (2002) [arXiv:hep-ph/0111224]. P. Huber, T. Schwetz and J. W. F. Valle, Phys. Rev. D **66**, 013006 (2002) [arXiv:hep-ph/0202048].